Claims:

1. A method for detecting anomalous phase measurements in a satellite differential navigation system in which a first satellite receiver and a second satellite receiver each compute phase measurements on a plurality of satellite channels, said method comprising the steps, performed for each of a plurality of iterations, of:

a) generating a combined phase difference vector;

b) generating a phase mismatch vector representing the difference between said combined phase difference vector and an estimated combined phase difference vector;

c) generating an averaged estimate vector representing the averaged estimate of said phase mismatch vector over said channels;

d) generating a residual vector representing the difference between said phase mismatch vector and said averaged estimate vector;

e) generating a vector of controlling signals by linear transformation of said residual vector and said averaged estimate vector;

f) generating said estimated combined phase difference vector by successively storing components of said vector of controlling signals for each of said channels; and

g) detecting anomalous phase measurements by analyzing said residual vector.

2. The method of claim 1 wherein said combined phase difference vector $\mathbf{\Phi c}$ comprises phase differences $(\Phi c_1..\Phi c_j..\Phi c_N)$ for a *j-th* satellite channel, and wherein step a) of generating a combined phase difference vector further comprises the step of:

calculating said phase difference vector $\mathbf{\Phi c}$ as $\mathbf{\Phi c} = \mathbf{\Phi}^{\mathbf{B}} - \mathbf{\Phi}^{\mathbf{R}}$ where vector $\mathbf{\Phi}^{\mathbf{B}}$ comprises the full phases measured by one of said satellite receivers for each *j-th* satellite channel $(\Phi_{B1}..\Phi_{Bj}..\Phi_{BN})$ and vector $\mathbf{\Phi}^{\mathbf{R}}$ comprises the full phases measured by the other satellite receiver for each *j-th* satellite channel $(\Phi_{R1}..\Phi_{Rj}..\Phi_{RN})$.

3. The method of claim 1 wherein said first and second satellite receivers are dual frequency (f1 and f2) receivers and wherein said combined phase difference vector $\mathbf{\Phi c}$ comprises phase differences $(\Phi c_1..\Phi c_j..\Phi c_N)$ for a *j-th* satellite channel, and wherein step a) of generating a combined phase difference vector further comprises the step of:

calculating said phase differences Φc_j of said phase difference vector $\mathbf{\Phi c}$ as

$\Phi c_j = (\Phi^B_{2j} - \Phi^R_{2j}) - (\Phi^B_{1j} - \Phi^R_{1j})(f2 / f1)$

where Φ^B_{2j} and Φ^B_{1j} represent the full phase measured by one of the satellite receivers at each *j-th* satellite channel at frequencies f2 and f1 respectively, and

where Φ^R_{2j} and Φ^R_{1j} represent the full phase measured by the other of the satellite receivers at each *j-th* satellite channel at frequencies f2 and f1 respectively.

4. The method of claim 1 wherein said step c) of generating an averaged estimate vector **ΔΨ** further comprises the step of:

calculating said average estimate vector **ΔΨ** as

$$\Delta\Psi = \left(\sum_{j=1}^{N} w_j \cdot \Delta\Phi c_j \right) / \left(\sum_{j=1}^{N} w_j \right)$$

where $\Delta\Phi c_j$ represents the components of said phase mismatch vector for a *j-th* satellite channel, w_j represents a weight coefficient for each *j-th* satellite channel, and N represents the number of satellite channels.

5. The method of claim 1 wherein step c) of generating an averaged estimate vector **ΔΨ** further comprises the step of:

calculating said average estimate vector **ΔΨ** as $\mathbf{\Delta\Psi} = \mathbf{H} \cdot \mathbf{G} \cdot \mathbf{\Delta\Phi c}$ where **H** is a matrix of directional cosines, **ΔΦ c** represents said phase mismatch vector, and **G** is a matrix defined by $\mathbf{G}=(\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H})^{-1}\mathbf{H}^T\mathbf{R}^{-1}$ where **R** is a covariance matrix of phase mismatches.

6. The method of claim 1 wherein said step e) of generating a vector of controlling signals further comprises the step of:

generating said vector of controlling signals in combined loop filters of each of said plurality of channels.

7. The method of claim 6 where each of said combined loop filters generates a control signal (U_{cj}) for a *j-th* channel according to the following:

$$U_{1j}(i) = \sum_{k=0}^{i} \gamma \delta_j(k)$$

$$U_{2j}(i) = \beta\,\delta_j(i) + U_{1j}(i)$$

$$U_{3j}(i) = \sum_{k=0}^{i} U_{2j}(k)$$

$$U_{cj}(i) = \Delta\Psi_j(i) + \alpha\delta_j(i) + U_{3j}(i) + V_{prj}(i)$$

where $V_{prj}(i)$ is a predicted value computed on the basis of a priori data, and α, β, γ are coefficients of the loop filter.

8. The method of claim 7 wherein said coefficients are time dependent and form a Kalman-type filter.

9. The method of claim 7 wherein said coefficients are constants and define a third-order channel loop.

10. The method of claim 1 wherein said step g) of detecting anomalous phase measurements further comprises the steps of:

h) comparing residuals of said residual vector with a threshold; and

i) determining that a particular channel has an anomalous phase measurement if a residual associated with said particular channel exceeds said threshold.

11. The method of claim 10 wherein said step h) of comparing further comprises the step of comparing the absolute value of said residuals to said threshold, wherein said threshold is in the range of 0.2 to 0.25 cycles.

12. The method of claim 10 wherein said step g) of detecting anomalous phase measurements further comprises the steps of:

j) eliminating said particular channel from subsequent iterations of step a); and

repeating steps b) through j) until no residual exceeds said threshold or until a threshold number of said channels remain.

13. The method of claim 1 wherein said step g) of detecting anomalous phase measurements further comprises the steps of:

h) generating a weighted sum of residual squares for said channels;

i) comparing said weighted sum of residual squares to a threshold; and

j) determining that an anomalous phase measurement exists if said weighted sum of residual squares exceeds said threshold.

14. The method of claim 13 wherein said step g) of detecting anomalous phase measurements further comprises the step of:

k) determining that a particular channel has an anomalous phase measurement if a residual associated with said particular channel is the maximum residual in said residual vector.

15. The method of claim 14 wherein said step g) of detecting anomalous phase measurements further comprises the steps of:

l) eliminating said particular channel from subsequent iterations of step a); and

repeating steps b) through l) until said weighted sum of residual squares does not exceed said threshold or until a threshold number of said channels remain.

16. The method of claim 13 wherein said step g) of detecting anomalous phase measurements further comprises the steps of:

k) eliminating x channels from subsequent iterations of step a), varying the channels eliminated for each iteration of step k); and

repeating steps b) through k) until either said weighted sum of residual squares does not exceed said threshold or until x reaches a threshold, incrementing x by one after all combinations of channels for a given x have been eliminated during an iteration of step k).

17. The method of claim 1 wherein said steps are performed in one of said satellite receivers.

18. The method of claim 17 wherein said one satellite receiver receives phase measurements from the other satellite receiver.

19. The method of claim 1 further comprising the step of:

h) using information about said anomalous phase measurements detected in step g) in a navigation task.

20. The method of claim 19 further comprising the step of:

i) generating a cycle slip estimate for a channel determined to have an anomalous phase measurement and using said cycle slip estimate in said navigation task.

21. An apparatus for detecting anomalous phase measurements in a satellite differential navigation system in which a first satellite receiver and a second satellite receiver each compute phase measurements on a plurality of satellite channels, said apparatus comprising:

a combined phase difference generator for generating a combined phase difference vector;

means for generating a phase mismatch vector representing the difference between said combined phase difference vector and an estimated combined phase difference vector;

an integrated discriminator for generating an averaged estimate vector representing the averaged estimate of said phase mismatch vector over said channels;

means for generating a residual vector representing the difference between said phase mismatch vector and said averaged estimate vector;

at least one joint loop filter for generating a vector of controlling signals by linear transformation of said residual vector and said averaged estimate vector;

an accumulator for generating said estimated combined phase difference vector by successively storing components of said vector of controlling signals for each of said channels; and

a residuals analyzer for detecting anomalous phase measurements by analyzing said residual vector.

22. The apparatus of claim 21 wherein said combined phase difference vector $\mathbf{\Phi c}$ comprises phase differences $(\Phi c_1..\Phi c_j..\Phi c_N)$ for a *j-th* satellite channel, and wherein said phase difference generator generates said combined phase difference vector $\mathbf{\Phi c}$ as $\mathbf{\Phi c} = \mathbf{\Phi}^{\mathbf{B}} - \mathbf{\Phi}^{\mathbf{R}}$ where vector $\mathbf{\Phi}^{\mathbf{B}}$ comprises the full phases measured by one of said satellite receivers for each *j*-

th satellite channel $(\Phi_{B1}..\Phi_{Bj}..\Phi_{BN})$ and vector Φ^R comprises the full phases measured by the other satellite receiver for each *j-th* satellite channel $(\Phi_{R1}..\Phi_{Rj}..\Phi_{RN})$.

23. The apparatus of claim 21 wherein said first and second satellite receivers are dual frequency (f1 and f2) receivers and wherein said combined phase difference vector $\mathbf{\Phi c}$ comprises phase differences $(\Phi c_1..\Phi c_j..\Phi c_N)$ for a *j-th* satellite channel, and wherein said phase difference generator generates said phase differences Φc_j of said phase difference vector $\mathbf{\Phi c}$ as

$$\Phi c_j = (\Phi^B_{2j} - \Phi^R_{2j}) - (\Phi^B_{1j} - \Phi^R_{1j})(f2 / f1)$$

where Φ^B_{2j} and Φ^B_{1j} represent the full phase measured by one of the satellite receivers at each *j-th* satellite channel at frequencies f2 and f1 respectively, and where Φ^R_{2j} and Φ^R_{1j} represent the full phase measured by the other of the satellite receivers at each *j-th* satellite channel at frequencies f2 and f1 respectively.

24. The apparatus of claim 21 wherein said integrated discriminator generates said averaged estimate vector $\mathbf{\Delta\Psi}$ as

$$\Delta\Psi = \left(\sum_{j=1}^{N} w_j \cdot \Delta\Phi c_j \right) / \left(\sum_{j=1}^{N} w_j \right)$$

where $\Delta\Phi c_j$ represents the components of said phase mismatch vector for a *j-th* satellite channel, w_j represents a weight coefficient for each *j-th* satellite channel, and N represents the number of satellite channels.

25. The apparatus of claim 21 wherein said integrated discriminator generates said averaged estimate vector $\mathbf{\Delta\Psi}$ as $\mathbf{\Delta\Psi = H \cdot G \cdot \Delta\Phi c}$ where $\mathbf{H}$ is a matrix of directional cosines, $\mathbf{\Delta\Phi c}$ represents said phase mismatch vector, and $\mathbf{G}$ is a matrix defined by $\mathbf{G=(H^TR^{-1}H)^{-1}H^TR^{-1}}$ where $\mathbf{R}$ is a covariance matrix of phase mismatches.

26. The apparatus of claim 21 wherein said joint loop filter generates said vector of controlling signals in combined loop filters of each of said plurality of channels.

27. The apparatus of claim 26 wherein each of said at least one combined loop filters generates a control signal (U_{cj}) for a *j-th* channel according to the following:

$$U_{1j}(i) = \sum_{k=0}^{i} \gamma\, \delta_j(k)$$

$$U_{2j}(i) = \beta\, \delta_j(i) + U_{1j}(i)$$

$$U_{3j}(i) = \sum_{k=0}^{i} U_{2j}(k)$$

$$U_{cj}(i) = \Delta\Psi_j(i) + \alpha\delta_j(i) + U_{3j}(i) + V_{prj}(i)$$

where $V_{prj}(i)$ is a predicted value computed on the basis of a priori data, and α, β, γ are coefficients of the loop filter.

28. The apparatus of claim 27 wherein said coefficients are time dependent and form a Kalman-type filter.

29. The apparatus of claim 27 wherein said coefficients are constants and define a third-order channel loop.

30. The apparatus of claim 21 wherein said residuals analyzer detects anomalous phase measurements by comparing residuals of said residual vector with a threshold and determining that a particular channel has an anomalous phase measurement if a residual associated with said particular channel exceeds said threshold.

31. The apparatus of claim 21 wherein said residuals analyzer detects anomalous phase measurements by generating a weighted sum of residual squares for said channels, comparing said weighted sum of residual squares to a threshold, and determining that an anomalous phase measurement exists if said weighted sum of residual squares exceeds said threshold.

32. The apparatus of claim 31 wherein said residuals analyzer further detects anomalous phase measurements by determining that a particular channel has an anomalous phase measurement if a residual associated with said particular channel is the maximum residual in said residual vector.

33. A method for detecting anomalous phase measurements in a satellite differential navigation system in which a first satellite receiver and a second satellite receiver each compute phase measurements on a plurality of satellite channels, said method comprising the steps, performed for each of a plurality of iterations, of:

a) generating a combined phase difference vector;

b) generating an increment vector representing the difference between said combined phase difference vector and a combined phase difference vector of a preceding iteration,

c) generating an averaged increment estimate vector representing the averaged estimate of said increment vector;

d) generating an incremental residual vector representing the difference between said increment vector and said averaged increment estimate vector;

e) generating an integrated residual vector from said incremental residual vector; and

f) detecting anomalous phase measurements by analyzing said integrated residual vector.

34. The method of claim 33 wherein step a) of generating a combined phase difference vector $\mathbf{\Phi\, c(i)}$ further comprises the step of:

calculating said phase difference vector $\mathbf{\Phi\, c(i)}$ as $\mathbf{\Phi\, c(i) = \Phi^{B}(i) - \Phi^{R}(i) - \Phi^{BR}(i)}$ where vector $\mathbf{\Phi^{B}(i)}$ comprises the full phases measured by one of said satellite receivers for each *i-th* iteration and vector $\mathbf{\Phi^{R}(i)}$ comprises the full phases measured by the other satellite receiver for each *i-th* iteration and $\mathbf{\Phi^{BR}(i)}$ is a prediction of satellite movement.

35. The method of claim 33 wherein said step c) of generating an averaged increment estimate vector further comprises the step of:

calculating said average estimate vector $\Delta\hat{\Phi}$ as

$$\Delta\hat{\Phi}(i) = \mathbf{H(i) \cdot G(i) \cdot \Delta\Phi\, c(i)},$$

where $\Delta\hat{\Phi}(i)$ represents the components of said average estimate vector for an *i-th* iteration, **H** is a matrix of directional cosines, **G** is a matrix defined by $\mathbf{G=(H^{T}R^{-1}H)^{-1}H^{T}R^{-1}}$ where **R** is a covariance matrix of phase mismatches, and $\mathbf{\Delta\Phi\, c(i) = \Phi\, c(i) - \Phi\, c(i-1)}$ where $\mathbf{\Phi\, c(i)}$ is a vector of combined phase difference at each *i-th* iteration.

36. The method of claim 33 wherein said step e) of generating an integrated residual vector further comprises the step of generating integrated residuals $\boldsymbol{\delta}(\mathbf{i})$ as

$$\boldsymbol{\delta}(\mathbf{i}) = \mathrm{A} \cdot \boldsymbol{\delta}(\mathbf{i} - \mathbf{1}) + \boldsymbol{\Delta\delta}(\mathbf{i})$$

for each i-th iteration, where A is a coefficient in the range 0.995 … 0.999.

37. The method of claim 33 wherein said step f) of detecting anomalous phase measurements further comprises the steps of:

g) generating a weighted sum of integrated residual squares for said channels;

h) comparing said weighted sum of integrated residual squares to a threshold; and

i) determining that an anomalous phase measurement exists if said weighted sum of integrated residual squares exceeds said threshold.

38. The method of claim 37 wherein said step f) of detecting anomalous phase measurements further comprises the steps of:

j) eliminating x channels from subsequent iterations of step a), varying the channels eliminated for each iteration of step j); and

repeating steps b) through j) until either said weighted sum of integrated residual squares does not exceed said threshold or until x reaches a threshold, incrementing x by one after all combinations of channels for a given x have been eliminated during an iteration of step j).

39. The method of claim 33 wherein said steps are performed in one of said satellite receivers.

40. The method of claim 39 wherein said one satellite receiver receives phase measurements from the other satellite receiver.

41. The method of claim 33 further comprising the step of:

g) using information about said anomalous phase measurements detected in step f) in a navigation task.

42. The method of claim 41 further comprising the step of:

h) generating a cycle slip estimate for a channel determined to have an anomalous phase measurement and using said cycle slip estimate in said navigation task.

43. The method of claim 33 further comprising the steps of:

g) receiving channel indicator alarms from a channel indicator, said channel indicator alarms marking channels with anomalous phase measurements;

h) eliminating channels marked with channel indicator alarms from subsequent iterations of step a); and

i) repeating steps a) through f).

44. The method of claim 43 wherein said step f) of detecting anomalous phase measurements further comprises the steps of:

j) generating a weighted sum of integrated residual squares for said channels;

k) comparing said weighted sum of integrated residual squares to a threshold; and

l) determining that an anomalous phase measurement exists if said weighted sum of integrated residual squares exceeds said threshold.

45. An apparatus for detecting anomalous phase measurements in a satellite differential navigation system in which a first satellite receiver and a second satellite receiver each compute phase measurements on a plurality of satellite channels, said apparatus comprising:

a) a combined phase difference generator for generating a combined phase difference vector;

b) means for generating an increment vector representing the difference between said combined phase difference vector and a combined phase difference vector of a preceding measurement,

c) an integrated converter for generating an averaged increment estimate vector representing the averaged estimate of said increment vector;

d) means for generating an incremental residual vector representing the difference between said increment vector and said averaged increment estimate vector;

e) a digital filter for generating an integrated residual vector from said incremental residual vector; and

f) a residuals analyzer for detecting anomalous phase measurements by analyzing said integrated residual vector.

46. The apparatus of claim 45 wherein said combined phase difference generator generates said combined phase difference vector $\mathbf{\Phi\,c(i)}$ as $\mathbf{\Phi\,c(i) = \Phi^{B}(i) - \Phi^{R}(i) - \Phi^{BR}(i)}$ where vector $\mathbf{\Phi^{B}(i)}$ comprises the full phases measured by one of said satellite receivers for each *i-th* iteration and vector $\mathbf{\Phi^{R}(i)}$ comprises the full phases measured by the other satellite receiver for each *i-th* iteration and $\mathbf{\Phi^{BR}(i)}$ is a prediction of satellite movement.

47. The apparatus of claim 45 wherein said integrated converter generates said averaged increment estimate vector $\Delta\hat{\Phi}$ as

$$\Delta\hat{\Phi}\ (i) = \mathbf{H(i) \cdot G(i) \cdot \Delta\Phi\,c(i)},$$

where $\Delta\hat{\Phi}\ (i)$ represents the components of said average estimate vector for an *i-th* iteration, $\mathbf{H}$ is a matrix of directional cosines, $\mathbf{G}$ is a matrix defined by $\mathbf{G=(H^{T}R^{-1}H)^{-1}H^{T}R^{-1}}$ where $\mathbf{R}$ is a covariance matrix of phase mismatches, and $\mathbf{\Delta\Phi\,c(i) = \Phi\,c(i) - \Phi\,c(i-1)}$ where $\mathbf{\Phi\,c(i)}$ is a vector of combined phase difference at each *i-th* iteration.

48. The apparatus of claim 45 wherein said residuals analyzer detects anomalous phase measurements by generating a weighted sum of integrated residual squares for said channels, comparing said weighted sum of integrated residual squares to a threshold, and determining that an anomalous phase measurement exists if said weighted sum of integrated residual squares exceeds said threshold.

49. The apparatus of claim 45 wherein said digital filter generates integrated residuals $\boldsymbol{\delta}\mathbf{(i)}$ as

$$\boldsymbol{\delta}\mathbf{(i)} = \mathrm{A} \cdot \boldsymbol{\delta}\mathbf{(i-1)} + \boldsymbol{\Delta\delta}\mathbf{(i)}$$

for each of an i-th iteration, where A is a coefficient in the range 0.995 … 0.999.

50. A method for detecting anomalous phase measurements in a satellite differential navigation system in which a first satellite receiver and a second satellite receiver each compute

phase measurements on a plurality of satellite channels, said method comprising the steps, performed for each of a plurality of iterations, of:

a) generating a combined phase difference vector;

b) generating an increment vector representing the difference between said combined phase difference vector and a combined phase difference vector of an initial measurement at an initial time,

c) generating a corrected increment vector using a cycle slip correction estimate generated in a preceding iteration;

d) analyzing channel indicator alarms;

e) generating an averaged increment estimate vector representing the averaged estimate of said corrected increment vector using channels not associated with a channel indicator alarm;

f) generating a residual vector representing the difference between the corrected increment vector and the averaged increment estimate vector; and

g) generating said cycle slip correction estimate using said residual vector.

51. The method of claim 50 wherein said step a) of generating a combined phase difference vector further comprises the step of:

including a prediction of phase difference in said difference.

52. The method of claim 50 wherein said initial time is reset periodically.

53. The method of claim 50 further comprising the step of:

h) using said cycle slip correction estimate in a navigation task.

54. An apparatus for detecting anomalous phase measurements in a satellite differential navigation system in which a first satellite receiver and a second satellite receiver each compute phase measurements on a plurality of satellite channels, said apparatus comprising:

a) a combined phase difference generator for generating a combined phase difference vector;

b) means for generating an increment vector representing the difference between said combined phase difference vector and a combined phase difference vector of an initial measurement at an initial time;

c) a cycle slip correction unit for generating a cycle slip correction estimate;

d) means for generating a corrected increment vector using a cycle slip correction estimate generated in a preceding measurement;

d) a channel indicator analyzer for analyzing channel indicator alarms;

e) an integrated converter for generating an averaged increment estimate vector representing the averaged estimate of said corrected increment vector using channels not associated with a channel indicator alarm;

f) means for generating a residual vector representing the difference between the corrected increment vector and the averaged increment estimate vector; and

g) a correction unit for generating said cycle slip correction estimates using said residual vector.

55. The apparatus of claim 54 wherein said combined phase difference generator further generates said combined phase difference vector by including a prediction of phase difference in said difference.

56. The apparatus of claim 54 wherein said initial time is reset periodically.